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ORIGINAL ARTICLE

The effects of Amazon deforestation on non-timber forest products

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Abstract

The relationships between deforestation and non-timber forest products (NTFPs) supply chains are investigated in 532 municipalities throughout the Brazilian Amazon. The NTFP production of acai berry (*Euterpe* spp.), andiroba (*Carapa* spp.), Brazil nut (*Bertholletia excelsa* Bonpl.), and tonka bean (*Dipteryx* spp.) has reduced with increasing deforestation rates ($p < 0.02$). Correlations between the presence of NTFP extractivism and agroforestry systems and increased deforestation ranged between −22 and −38%. Forests suffering extractivism activities have decreased mainly in municipalities located in the southern and eastern Brazilian Amazon areas. These decreases are discussed as being associated to forest biomass, fragmentation, edge effect, wildfire, and climate change attributed to deforestation. However, increasing deforestation rates did not influence either cupuassu (*Theobroma grandiflorum* (Willd. ex Spreng.) K. Schum.) production ($p = 0.26$) or the presence of raw material processing businesses until 2017 ($p = 0.09$). The lack of observed associations between deforestation and cupuassu production is linked to NTFP management in agroforestry systems. NTFP flows from less deforested regions to municipalities that house factories for the production of oils, fats, pulp and dehydrated seeds. The productive andiroba and tonka bean chains are highly threatened by deforestation. Without the presence of forest restoration efforts employing agroforestry systems, the social and economic activities of both people and businesses are at risk, and NTFP production and diversity are increasingly reduced by Amazon deforestation.

Keywords Amazon land use · Climate change · Environmental change · Non-timber forest products · Supply chain · Tropical forest

Introduction

Some tropical forest plant species produce organic matter with high economic value, termed non-timber forest products (NTFPs). NTFPs are used by both people and businesses to generate human food and well-being, as well as forest conservation and profits (Lopes et al. 2021; Vidal et al. 2021). The primary net NTFP forest production economic potential is estimated as US\$ 697,79 ha^{-1} $year^{-1}$ (Peters et al. 1989), while extractivism activities generate an average of US\$ 57 ha^{-1} $year^{-1}$ considering only acai berry (Lopes et al. 2019). NTFPs represent 42% of the average annual household income, at US\$ 3392, when combining extractivism activities, agroforestry systems, and the infrastructure to produce vegetable oil for the cosmetics supply chain (Antunes et al. 2021). Forest extractivism and NTFP cultivation in agroforestry systems are estimated as generating close to US\$ 2 billion $year^{-1}$ in the Brazilian Amazon (IBGE 2019a b).

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Deforestation comprises the conversion of forests to another form of land use or forest cover decreases to below 10% for a long period of time (FAO 2001). The average Brazilian Amazon deforestation rate between 1988 and 2020 is estimated as $13{,}856 \pm 6{,}578$ km^2 year^{-1} (INPE 2020). Accumulated Brazilian Amazon deforestation has reduced the forest biomass in over 750,000 km^2 (Nobre et al. 2016). Changes in land use have reduced organic matter production through photosynthesis (von Randow et al. 2004), resulting in higher carbon emissions to the atmosphere (Gatti et al. 2021). Climate changes caused by deforestation have reduced atmospheric and soil water retention (Gash and Nobre 1997) leading to forest dry-out and changes in floristic composition (Barlow and Peres 2008; Esquivel-Muelbert et al. 2019). Furthermore, Amazon seed and fruit production have also been altered by deforestation (Hawes et al. 2020; Jakovac et al. 2021).

Amazon deforestation effects on NTFP and raw material production have been investigated for some species at the local and regional scales (Costa and Nunez 2017; Jansen et al. 2021). NTFP processes and supply chains flows are not yet well understood (Lambert and Cooper 2000; Costa 2019), so local populations, consumers, and traders may find it difficult to understand how deforestation may affect their social and economic activities. NTFP extraction and cultivation are economic activities carried out by indigenous peoples, riverine communities, Amazonian mestizos, smallholder farmers, and other culturally distinct populations who have access to the Amazon's biodiversity (Barata 2012; Camilotti et al. 2020). Both economic activities and all the aforementioned populations are threatened as a result of deforestation (Shanley and Luz 2003; Scoles et al. 2016; Hooper and Ashton 2020). Even so, scarce research on the relationship between deforestation and NTFP supply chains in the Amazon is available (Homma et al. 2000; Nobre et al. 2016; Lagneaux et al. 2021).

To assess whether supply chain activities and deforestation in the Amazon are interconnected, we mapped and characterized the NTFP production of several species, i.e., acai berry (*Euterpe* spp.), andiroba (*Carapa* spp.), Brazil nut (*B. excelsa*), tonka bean (*Dipteryx* spp.), and cupuassu (*T. grandiflorum*). The representative maps both NTFP (seeds and fruits) and raw material production (oils, fats, pulp, and dehydrated seeds) are presented for 532 evaluated municipalities. Potential relationships between supply chain activities and deforestation are analyzed, and their implications for people and businesses are discussed. We conclude with considerations on the need for forest restoration employing agroforestry systems to conserve NTFP production in the Amazon.

It is important to understand deforestation effects on NTFP to create strategies to adapt to environmental changes (Lapola et al. 2018; Gomes et al. 2019). Therefore, assessments that examine supply chains are relevant to different organizations who make use of Amazon plants, such as indigenous associations, extractive cooperatives, governmental organizations, and national and international businesses (Lima et al. 2020; Evangelista-Vale et al. 2021). These studies can contribute to policies surrounding biodiversity use and conservation in tropical forests while also providing a basis for similar studies on other NTFP.

Methods

Study area

The study area is located in the Brazilian Amazon (Fig. 1a). The region is mainly covered by equatorial forests, open ombrophilous forests, and white-sand vegetation (IBGE 2004; Arruda et al. 2017). The delimited area includes 553 municipalities and occupies a total area of approximately 4 million km^2 (Fig. 1b). All investigated municipalities are located in Brazil, in a region that either partially or totally covers the states of Acre (AC), Amapá (AP), Amazonas (AM), Mato Grosso (MT), Pará (PA), Rondônia (RO), Roraima (RR), Tocantins (TO), and Maranhão (MA) (Fig. 1c). Some of the investigated municipalities exhibit some areas covered by non-forest vegetation (Fig. 1a). Most of the municipalities are located in northern Roraima, eastern Amapá, northeast of the island of Marajó, in the state of Pará, and in the transition area from the dominant Amazon vegetation to the Cerrado vegetation, in central Brazil. A total of 532 municipalities were mapped, whose territories are either completely or mostly located within the Brazilian Amazon borders (Fig. 1b).

Mapping and characterization of supply chains

Data from the National Institute of Science and Technology for Climate Change was used to support the spatial and temporal Amazon NTFP supply chains analyses in 2017 (INCT-MC 2017). The main source of information for the INCT-MC database is the Brazilian Institute of Geography and Statistics (IBGE 2017a, b), that provides annual information on NTFP concerning acai berry, andiroba, Brazil nut, and tonka bean extractivism and/or agricultural production. It does not, however, provide data on cupuassu production or on raw material processing businesses in the investigated municipalities.

The municipalities that do carry out cupuassu NTFP production and house raw material production businesses are identified in the INCT-MC (2017) database following a technical and scientific literature review and 31 semi-structured interviews with stakeholders concerning supply chain activities. The interviews were carried out with the representatives

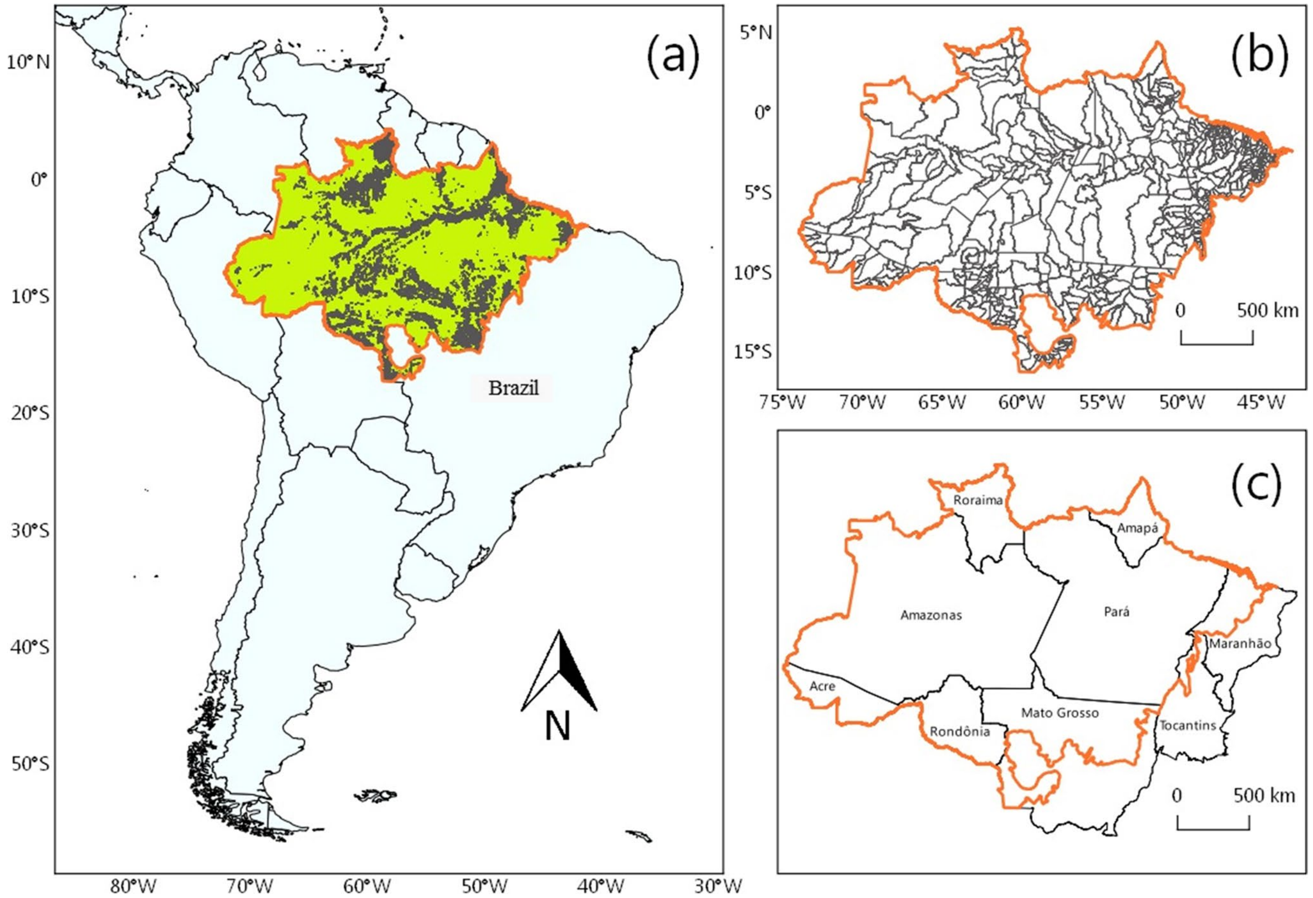


Fig. 1 Study area delimited by the orange line: **a** South America with emphasis on the dominance of the Amazon forest in green and non-forest areas in gray, **b** municipalities in the Brazilian Amazon, and **c** states comprising the Legal Amazon in Brazil in 2017

of 10 associations and cooperatives, seven state secretariats, six third sector organizations, five private businesses, and three research institutions. Respondents comprised individuals involved in the supply chain operations of the investigated species in 2017.

The plotted maps are representative of the absence/presence of economic NTFP and raw material production in the analyzed municipalities. NTFP production is characterized by the extractivism and/or cultivation of seeds and fruits from the evaluated species in agroforestry systems. Raw material production is represented by the presence of businesses with both the infrastructure and technology to transform the NTFP of the species evaluated herein into oils, fats, pulp, and dehydrated seeds to serve both the Brazilian and global market. Businesses that artisanally produce raw material for local commerce were not considered in the mapping.

NTFP and raw material production is represented in the plotted maps considering the territorial limits of each municipality in 2017. The maps were created using the QGIS software and drawn in SIRGAS 2000 (EPSG 4674). Map representations were plotted per species and overlay. The supply chains per species and in general considered both the mapping results and a technical and scientific literature review (Online Resource 1).

Deforestation data

Deforestation estimates for each municipality were obtained from the Legal Amazon Monitoring Program through the PRODES operating system (INPE 2020). This system uses satellite monitoring to provide annual information on forest losses due to forest clear-cutting. PRODES information is processed by the National Institute for Space Research and its partners (Assis et al. 2019). Deforestation data are presented per municipality and refer to both percentile and absolute values up to 2017, although only percentile deforestation values were used to test potential relationships between NTFP and raw material production in the investigated municipalities.

Testing for potential relationships between supply chains and deforestation

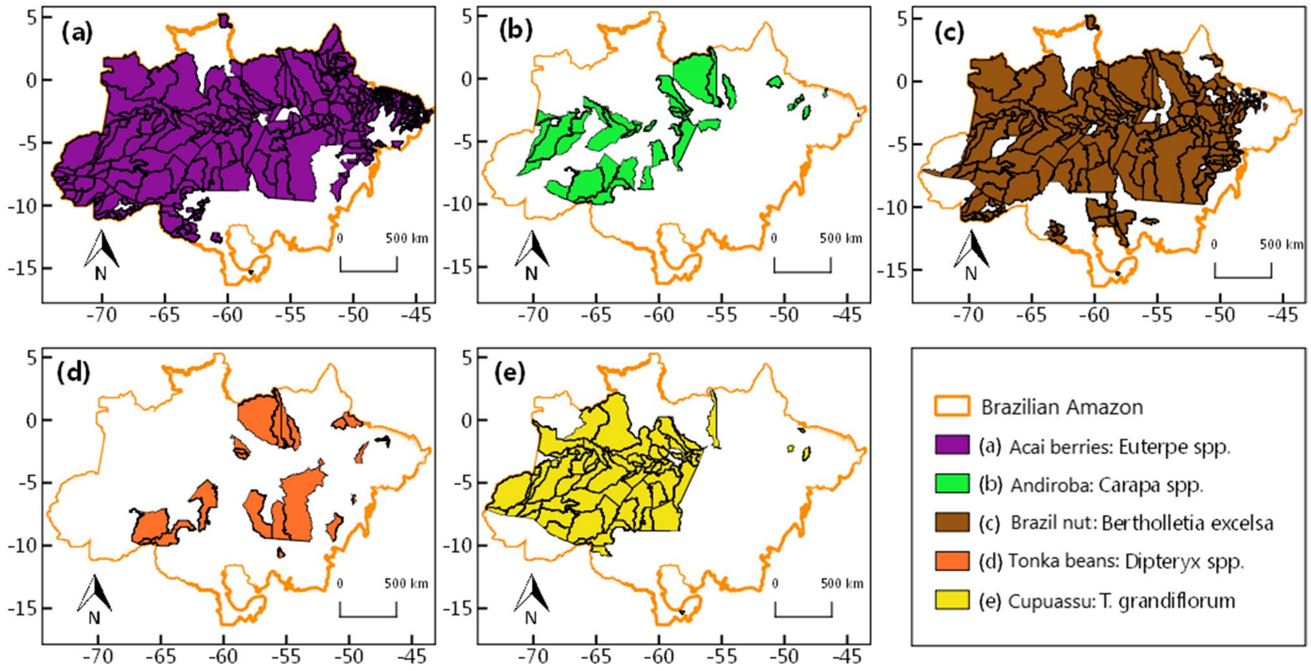
The Generalized Linear Mixed Model (GLMM) fit by maximum likelihood was used to test whether NTFP (seeds and fruits) and raw material production (oils, fats, pulp, and dehydrated seeds) are associated to the deforestation percentages of each investigated municipality. Deforestation was considered the fixed explanatory variable and the Brazilian Amazon states together as a random explanatory variable (Zuur et al. 2009, 2010, 2013). These analyses were carried out employing a binominal data distribution (absence/presence), which considers the absence of production as 0 and presence of production in the analyzed municipalities as 1, according to the mapping results. One analysis was performed applying a binominal data distribution for each studied species, followed by a Poisson distribution analysis, as processing businesses were present in only some of the investigated municipalities in 2017. Thus, the count for each municipality ranged between 0 and 5, with 0 indicating lack of information on raw material processing businesses and 5 indicating evidence of raw material processing for all studied species. Thus, six GLMM analyses were performed to test the significance between deforestation and the presence of NTFP production and raw material. All analyses were performed with an alpha value set at 5% using the LME4, ROCR, and InformationValue packages available in the R software (Bates et al. 2015; Hoo et al. 2017). The occurrence probabilities were identified for each of the 532 evaluated municipalities for the entire NTFP set. The probability of occurrence values that range between 0 and 1 was calculated and graphically represented alongside significant relationships.

NTFP production estimates were also calculated, as well as the means and standard deviations of the municipalities within the supply chains. The fixed effects of deforestation on NTFP and raw material production were estimated and discussed. The models are presented with their respective parameters and ROC curve. The area under the ROC curve (AUROC) is a measure of the model's ability to discriminate whether NTFP/raw material production is present or not in municipalities considering deforestation percentages. An AUROC of 0.5 represents a model presenting a discrimination capacity no better than chance, while an AUROC of 1.0 represents a perfect discrimination (Hoo et al. 2017). The database (Online Resource 2) and the script (Online Resource 3) containing the analyses are available in the supplementary material.

Results

Non-timber forest products supply chains

The presence of NTFP production for commercial purposes obtained through extractivism or agroforestry system activities was mapped for 331 municipalities throughout the Brazilian Amazon in 2017 (Fig. 2). No information was found on the NTFP production of 201 of the 532 assessed municipalities. The means and standard deviation estimates of the number of municipalities presenting NTFP production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(a) Acai berries: Euterpe spp.
(b) Andiroba: Carapa spp.
(c) Brazil nut: Bertholletia excelsa
(d) Tonka beans: Dipteryx spp.
(e) Cupuassu: T. grandiflorum

Fig. 2 Maps concerning extractivism and/or agroforestry systems of seeds and fruits in Brazilian Amazon municipalities (2017): **a** acai berry, **b** andiroba, **c** Brazil nut, **d** tonka bean, and **e** cupuassu

of acai berry, andiroba, Brazil nut, tonka bean, and cupuassu were 303 ± 11, 37 ± 5, 186 ± 11, 22 ± 5, and 63 ± 4, respectively.

Raw material production takes place in 57 Brazilian Amazon municipalities (Fig. 3). No raw material processing businesses were detected in 475 of the 532 assessed municipalities. The probability of a municipality presenting a raw material processing company for any of the studied species is 0.15. A more detailed characterization of the production chains for the investigated species is provided as a complement to the results presented in this assessment (Online Resource 1).

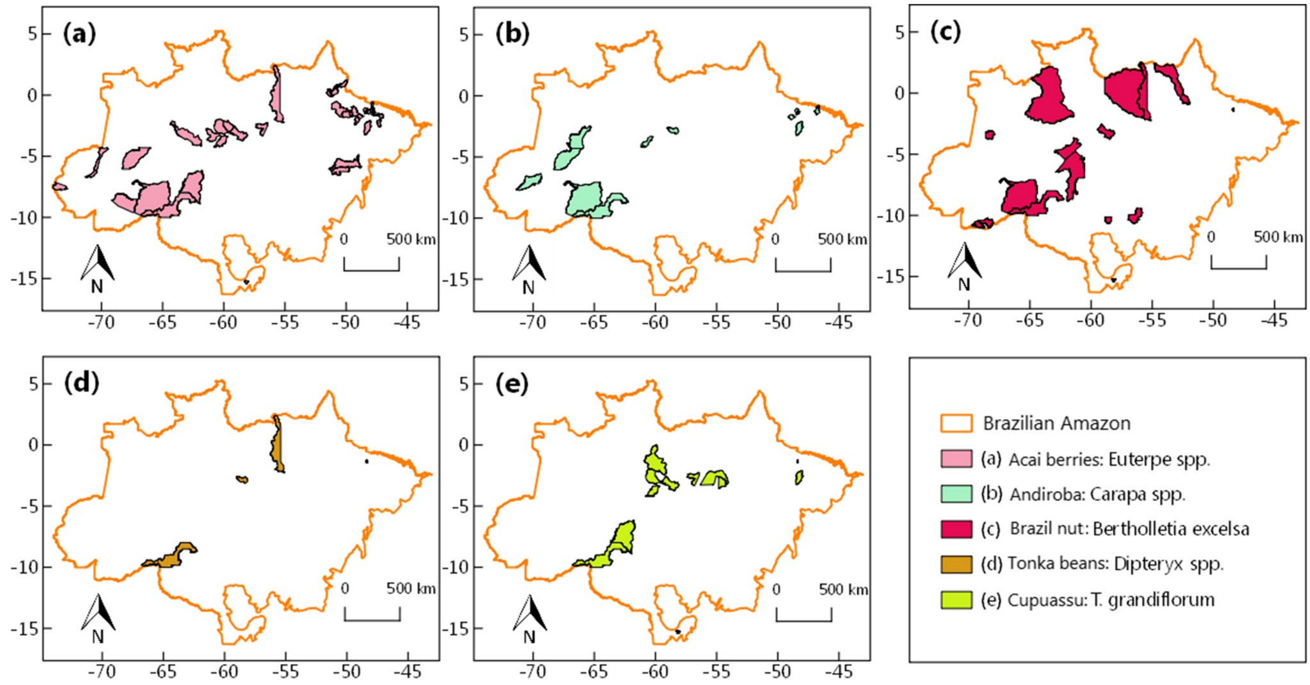
Relationships between supply chains and deforestation

The probability of NTFP production of acai berry, andiroba, Brazil nut, and tonka bean species decreases with increasing deforestation rates in the investigated municipalities. The correlations between fixed deforestation effects and NTFP andiroba and tonka bean production are higher compared to the acai berry and Brazil nut productions (Table 1). The probability of NTFP production for acai berry and Brazil nut in municipalities displaying high rates of deforestation is higher compared to andiroba and tonka bean productions (Fig. 4). No significant relationships between deforestation percentages and cupuassu NTFP production or to the presence of raw material processing businesses in the 532 analyzed municipalities are observed.

Deforestation rates are the highest in municipalities located in the southern and eastern Brazilian Amazon regions. This was noted when evaluating the official deforestation data made available by the National Institute for Space Research. It is important to note that the absence of information on NTFP production is concentrated in municipalities located on the southern and eastern edges of the forest (Fig. 5).

NTFP production for all studied species occurs simultaneously in only four municipalities, São Sebastião do Uatumã (AM), Silves (AM), Lábrea (AM) and Óbidos (PA). Deforestation rates in these municipalities were less than 15% in 2017. NTFP production for four species simultaneously has taken place in 26 municipalities, which exhibited deforestation rates of less than 60%, although most (21 municipalities) exhibited less than 15% deforestation. However, no NTFP production in six municipalities when considering deforestation rates ranging between 0 and 10% was observed. The 30 municipalities where NTFPs are produced concerning all or almost all investigated species are located mainly in the states of Amazonas and Pará (Fig. 6).

The observed point dispersion pattern demonstrates the spatial dependence of the analyzed municipalities (Fig. 6). For example, municipalities in Amazonas exhibited the highest average original forest cover (92% in 2017) and more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Brazilian Amazon
(a) Acai berries: Euterpe spp.
(b) Andiroba: Carapa spp.
(c) Brazil nut: Bertholletia excelsa
(d) Tonka beans: Dipteryx spp.
(e) Cupuassu: T. grandiflorum

Fig. 3 Maps concerning raw material processing businesses in Brazilian Amazon municipalities in 2017: **a** acai berry, **b** andiroba, **c** Brazil nut, **d** tonka bean, and **e** cupuassu

Table 1 Summary of the absence/presence of extractivism and/or agroforestry systems of seeds and fruits (NTFP) and number of raw material processing businesses estimated by Generalized Linear Mixed Model performed with deforestation percentages as fixed effects in 532 Brazilian Amazon municipalities in 2017. Estimates of non-significant relationships are not shown (*)

Response variables	Data distribution	Intercept (standard error)	Slope (standard error)	*p*-value	Correlation of fixed effects (%)
Acai berry NTFP (*Euterpe* spp.)	Binomial	0.863 (1.109)	−0.014 (0.005)	<0.01	−0.224 (−22%)
Andiroba NTFP (*Carapa* spp.)	Binomial	−3.326 (1.090)	−0.026 (0.009)	<0.01	−0.365 (−36%)
Brazil nut NTFP (*B. excelsa*)	Binomial	−0.816 (0.809)	−0.018 (0.005)	<0.01	−0.285 (−28%)
Tonka bean NTFP (*Dipteryx* spp.)	Binomial	−3.411 (0.840)	−0.020 (0.008)	<0.02	−0.380 (−38%)
Cupuassu NTFP (*T. grandiflorum*)	Binomial	*	*	=0.26	*
Raw material processing businesses	Poisson	*	*	=0.09	*

exploited species, while the lowest percentages of forest cover are observed in municipalities in the state of Tocantins (16% in 2017), where no NTFP activities for the investigated species occur. Therefore, the employed GLMM was relevant in the analysis of fixed deforestation effects on NTFP and raw material production in the 532 studied municipalities. States effects on NTFP and raw material production were not analyzed.

The accuracy of the applied models in detecting NTFP production, representing the number of correct answers of the true presences and true absences of NTFP production concerning the estimated model parameters, ranged between 83 and 92%. AUROC measurements are as follows: 0.83 for tonka bean, 0.91 for acai berry and andiroba, and 0.92 for Brazil nut. These data indicate high model performance in the studied area for all evaluated NTFP.

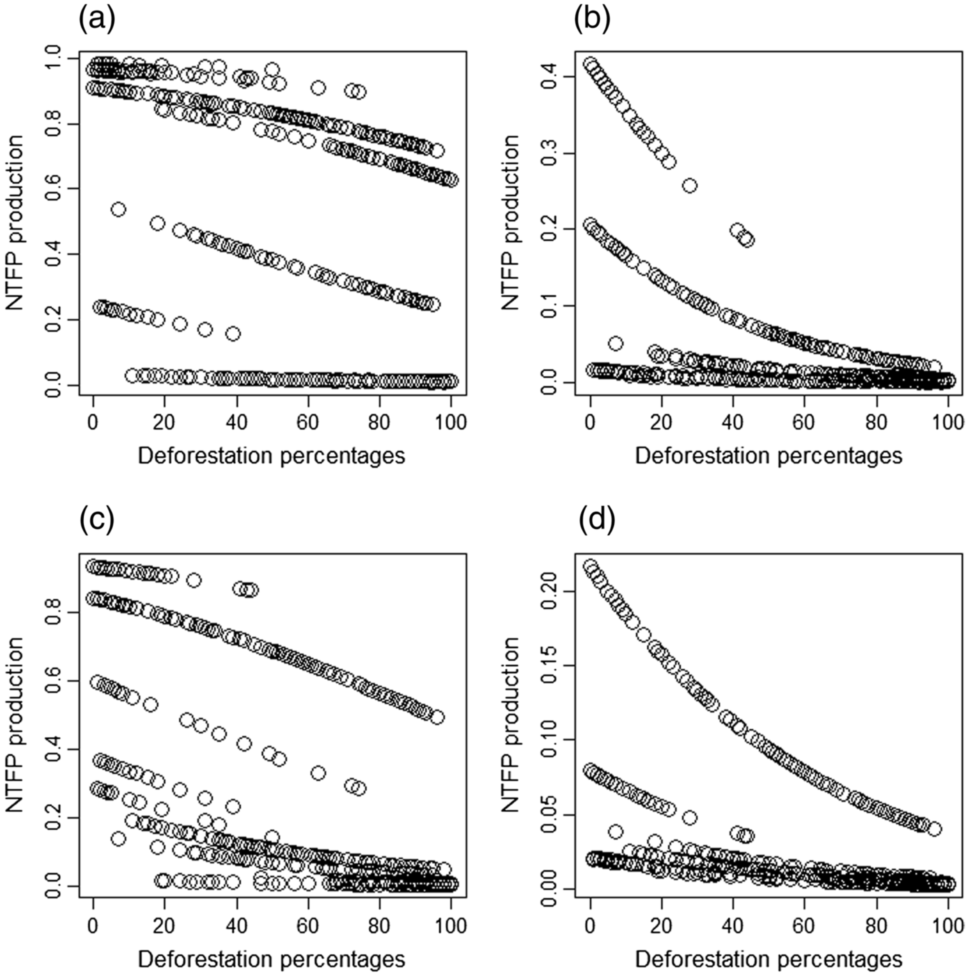

Fig. 4 Representation of the significant relationships between seed and fruit (NTFP) production and deforestation percentages in 532 municipalities in the Brazilian Amazon in 2017: **a** acai berry, **b** andiroba, **c** Brazil nut, and **d** tonka bean. Seed and fruit production estimates were obtained by Generalized Linear Mixed Model analyses

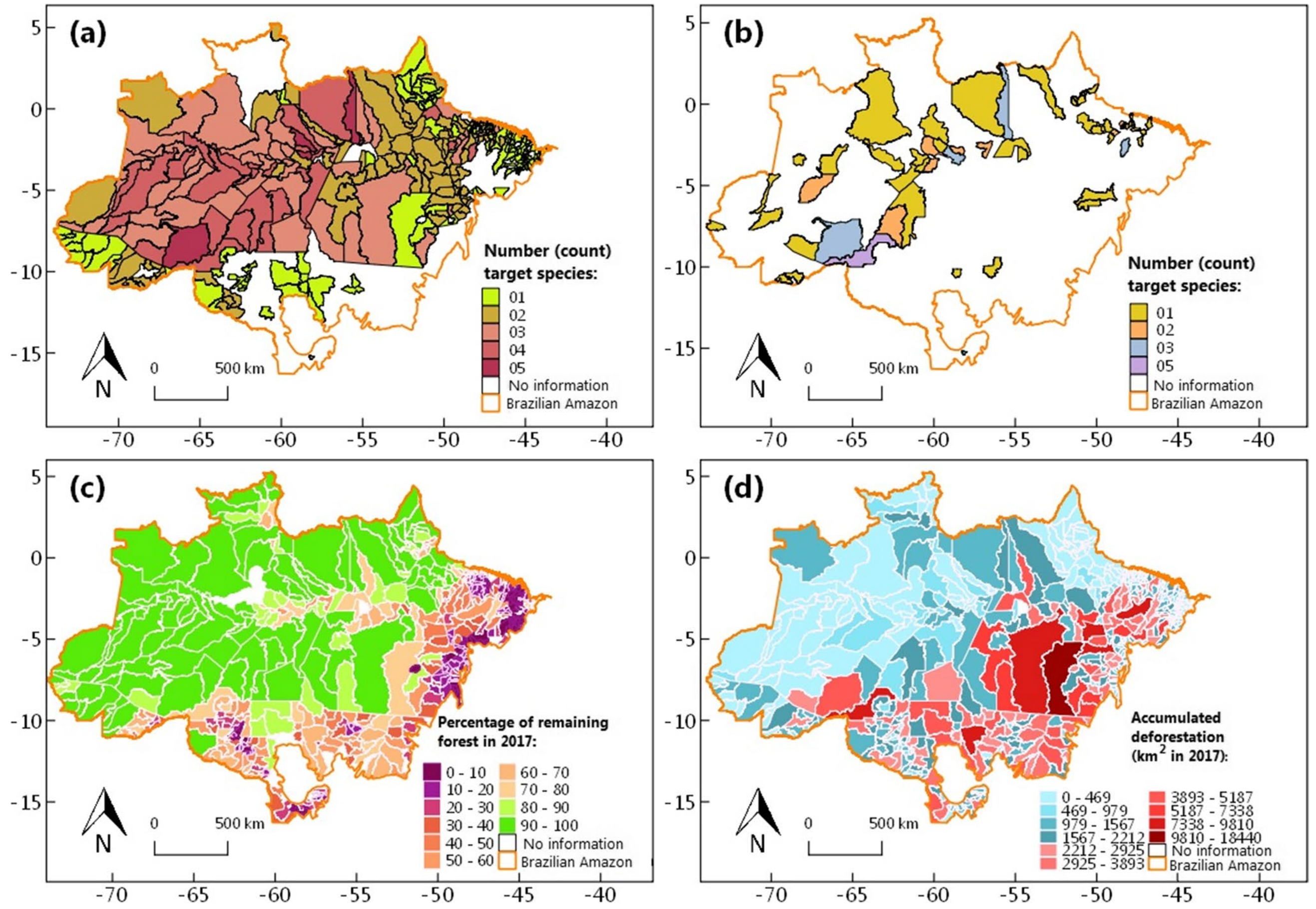

Fig. 5 Study area and the overlays of the results of seed and fruit production and raw material production mapping in 2017. Seed and fruit production (**a**), raw material processing businesses (**b**), percentage of original forest (**c**), and accumulated deforestation (**d**)

Discussion

Deforestation reduces Amazon seed and fruit production

Deforestation effects on NTFP production in tropical forests are known for some species at both local and regional scales. We expand this knowledge by analyzing large-scale NTFP productions and detecting a significant and negative deforestation effect on seed and fruit production in the investigated municipalities. Other factors may also explain the presence/absence of NTFP production, such as differences in environmental policies between states and municipalities, although they were not analyzed herein. The observed correlations between the presence/absence of NTFP production and deforestation percentages ranged between − 22 and − 38%. The models presented are reliable estimators of the presence or absence of NTFP productions when considering the deforestation percentages of the municipalities (Table 1).

Deforestation has reduced primary forest production by decreasing forest cover. When Amazon forests suffer deforestation, the means and standard deviations of aboveground biomass are reduced from 254.8 ± 103.2 to 52.9 ± 47.5 tons per hectare (Saatchi et al. 2007). Forest biomass reduction average area 1,385,000 ha^{-1} $year^{-1}$ between 1988 and 2020, with a peak of about 3,000,000 ha^{-1} in 1995 (INPE 2020). About 500 million trees and palms with trunks ≥ 10 cm in diameter are destroyed each year (Saatchi et al. 2007; Esquivel-Muelbert et al. 2019; INPE 2020). This may explain the results indicating that increasing deforestation rates reduces the number of municipalities involved in the NTFP production of acai berry, andiroba, Brazil nut, and tonka bean (Table 1).

Deforestation causes forest fragmentation, altering seed and fruit production. Fragments between 1 and 100 ha^{-1} disperse 3- to sixfold less seeds than continuous forests, and seed and fruit diversity has been reduced by up to ninefold with fragmentation (Hooper and Ashton 2020). Fragmentation is accelerating in the Amazon, and the number of fragments in the Brazilian Amazon has increased from 2,601 in 1976 to 38,270 in 2010 (Aragão et al. 2014). Therefore, more fragmented forests, as in the municipalities located in

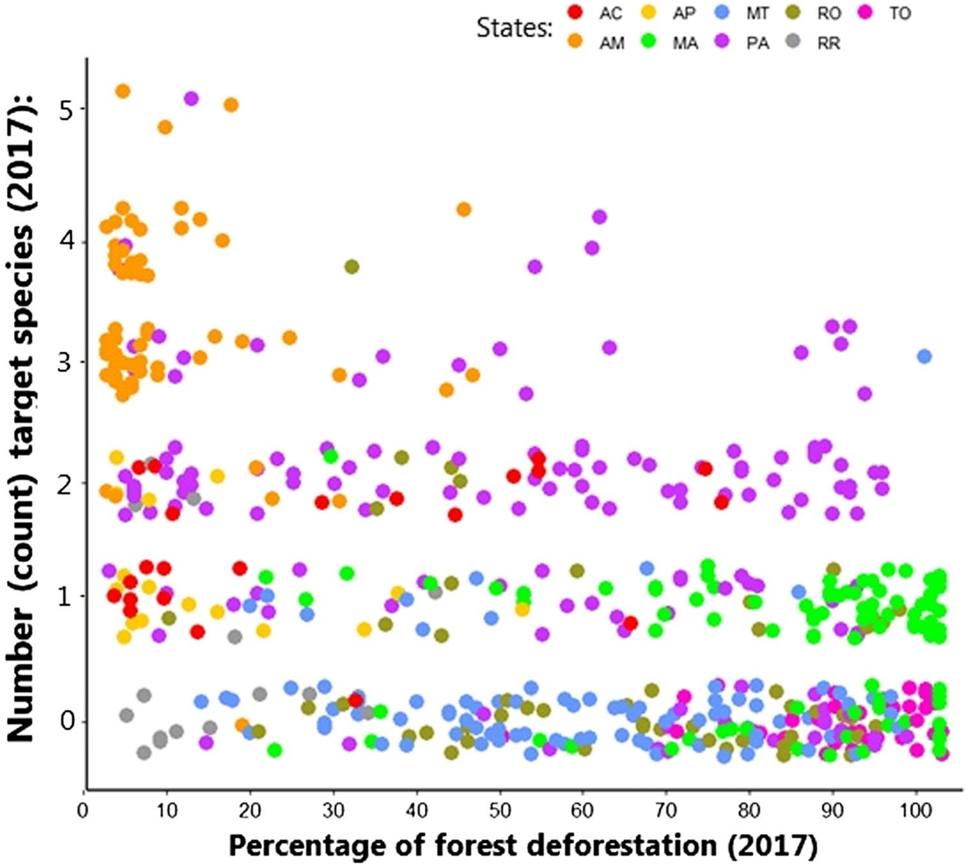

Fig. 6 Seeds and fruits production and deforestation percentage mapping in Brazilian Amazon municipalities. The dots on the graph represent the 532 analyzed municipalities. The colors of the dots indicate the diferent Brazilian Amazon states. The number of records for each target species in each municipality on the graph ranges from 0 to 5. Dispersion of the points on the vertical axis of the discrete number is illustrative, to reduce point overlap

the southern and eastern regions of the Brazilian Amazon, lead to decreased NTFP density and diversity.

The effect caused by non-forest edges intensifies NTFP decreases. The annual mortality rate of trees with trunks ≥ 60 cm in diameter increases by over 200% within 300 m of non-forest edges (Laurance et al. 2000). Brazil nut, andiroba, and tonka bean trees are over 60 cm in trunk diameter when they mature (Peres et al. 2003; Lorenzi and Matos 2008). Large trees are more exposed to the winds and are covered with vines (Laurance et al. 2001; Laurance and Curran 2008). The edge effect increases solar radiation forest entry and causes microclimate alterations, such as decreased atmospheric and soil water content, which favor wildfires (Silva Junior et al. 2018).

Wildfires in the Amazon are increasing in both deforested areas and in forests that do not suffer these activities (Aragão et al. 2018). Fire burns NTFP, which can be either regenerated, collected, or traded, and causes damage to the roots, trunk, and vegetation canopies, killing more trees than palms (Barlow and Peres 2008; Brando et al. 2019). Forests in the south and east are more vulnerable to wildfires (Aragão et al. 2018), as they are located in areas presenting lower average rainfall rates and longer dry seasons compared to forests in the western and northern Amazon regions (Nobre et al. 2016; Pontes-Lopes et al. 2021). Thus, wildfires intensify deforestation effects by reducing NTFP, especially in municipalities in the southern and eastern forest regions, corroborating our findings of a reduced number of species used in NTFP production in the most deforested municipalities.

Climate changes caused by deforestation lead to air heating in deforested areas. The mean albedo in forests is 0.13, increasing to 0.18 in pastures (Culf et al. 1995). Temperature increases of about 0.4 °C per decade from 1973 to 2013 have been observed in 95% of the meteorological stations located throughout the Brazilian Amazon (Almeida et al. 2016a). Sensible heat flux, amplitude, and average temperature are higher in pastures compared to forests (von Randow et al. 2004), and increasing temperatures reduce atmospheric and soil water retention and cause physiological effects on plants (Uhl and Kauffman 1990; Sánchez et al. 2014).

Observed increases in the abortion rates of flowers and fruits, comprising flower and fruit detachment from plants before they are pollinated and mature, have been attributed to increasing temperatures and atmospheric pressure vapor deficit (VPD) (López et al. 2021). Plants exposed to high VPD generally increase their transpiration rates and decrease stomatal conductance and photosynthesis (von Randow et al. 2004; López et al. 2021). Temperature variations also decrease glucose production (Haven et al. 2007). This compound is normally transformed into lipids and proteins during plant synthesis for NTFP production. Therefore, higher deforestation rates that result in lower NTFP production may also be linked to temperature increases and variations caused by deforestation.

On the other hand, no relationship between deforestation rates and cupuassu production was detected in the present study. Extractivists report, and later studies have confirmed, that NTFP decreases for many plant species occur municipalities where deforestation rates are high, and the timber sector is active (Shanley and Luz 2003). However, due to the natural characteristics of their wood, cupuassu trees are less employed by the timber sector (Homma 2014). In addition, cupuassu production takes place, mainly, in agroforestry systems, and planting efforts in these systems leads to more conserved NTFP (Homma 2014). In fact, cupuassu has become one of the most important species in terms of tree numbers and income generation in rural Amazon properties (Bolfe and Batistella 2011; Lagneaux et al. 2021). Therefore, the lack of any detected relationships between deforestation and cupuassu production may be associated to NTFP production in agroforestry systems and the lack of cupuassu tree suitability for the wood sector.

The mapping and findings carried out herein indicate that deforestation reduces NTFP production mostly in municipalities located under the vegetation cover categorized as open ombrophilous forest. This may indicate that soil and climate variations also influence plant productivity. In fact, open ombrophilous forest present lower wood density influenced by lower rainfall rates and increased VPD during the dry season (Arruda et al. 2017; Wagner et al. 2016). Thus, in addition to deforestation, natural factors such as lower rainfall rates and dry season duration may also be associated to NTFP productivity in municipalities located in the southern region of the Brazilian Amazon. Future studies may reveal how natural soil and climatic variations alter NTFP production in the region.

Deforestation implications for supply chains

The relationship between deforestation and supply chains was negative for most of the investigated species. Supply chains are defined by a set of processes, starting with basic inputs through to the development of a final product available to consumers, and include the production of raw material, industrialization, and commerce (Lambert and Cooper 2000; Costa 2019). Deforestation implications for individuals and businesses are debated considering multiple factors, such as productivity changes, floristic change, forest restoration, agroforestry systems, the risks of increased deforestation, and the need for further assessments. Further studies in this regard are important, as knowledge concerning supply chains is non-existent for most of the 15,000 species of identified Amazon trees and palms (Steege et al. 2015; Costa and Nunez 2017).

The framework presented herein may serve to support similar studies and broaden the view of the negative relationship between deforestation rates and Amazon NTFPs (Fig. 7). It includes land degradation and pollinator and disperser losses among several deforestation effects (Mesquita et al. 2015; Hooper and Ashton 2020; Jakovac et al. 2021), although they are not discussed in this study. Therefore, other deforestation effects that reduce primary forest production and economic potential of NTFP-providing plants exist in addition to those discussed herein.

Extractivists reduce their activities when NTFPs are reduced (Shanley and Luz 2003). For example, distance to access NTFPs and decreased productivity has discouraged extractivism in African forests (Mahonya et al. 2019). A geographical relationship in the Amazon between deforestation and highways, sawmills and soy, corn, and cotton planting of and pasture for cattle is observed (Almeida et al. 2016b; Nobre et al. 2016). Selective logging and agriculture reduce NTFP production and cause local species extinction (Milheiras and Mace 2019). This suggests that NTFP production has been replaced by logging and agriculture in the most deforested Amazon municipalities evaluated herein. Therefore, businesses may obtain less NTFP to use as raw material in their supply chains with less forests and extractivist activities.

Species composition in deforested and abandoned areas depends on land use history (i.e., soy cultivation or cattle ranching) (Jakovac et al. 2021). Species that increase in deforested and abandoned areas are generally less employed in NTFP supply chains. *Vismia* and *Cecropia* genera are two examples of species that increase in degraded forests. The former has increased in areas that suffer recurrent wildfires (Mesquita et al. 2015), while the latter has increased at a rate of 3.4% year^{-1} (Esquivel-Muelbert et al. 2019). Currently, NTFPs from these genera are much less valued compared to those from the species investigated in this study, perhaps due to a lack of consumers for NTFPs originated from *Vismia* and *Cecropia* species in the Amazon.

Forest restoration for native species that provide economically valuable NTFPs is rare in deforested Amazon areas (Homma 2014). Ecological restoration and natural regeneration projects are effective in increasing biodiversity and vegetation structure (Crouzeilles et al. 2017; Bustamante et al. 2019). Forest restorations with agroforestry systems for NTFP cultivation have generated long-term ecological and economic returns (Martorano et al. 2016; Gasparinetti et al. 2019; Lagneaux et al. 2021). Forest restoration is paramount for the conservation and enhancement of the biological, social, and economic importance of NTFPs (Chazdon 2008; Homma 2014; Lagneaux et al. 2021).

The economic potential of extractivist activities seems less threatened in municipalities in the western and northern forest regions, where deforestation rates are lower and rainfall rates are higher. The lack of relationships between

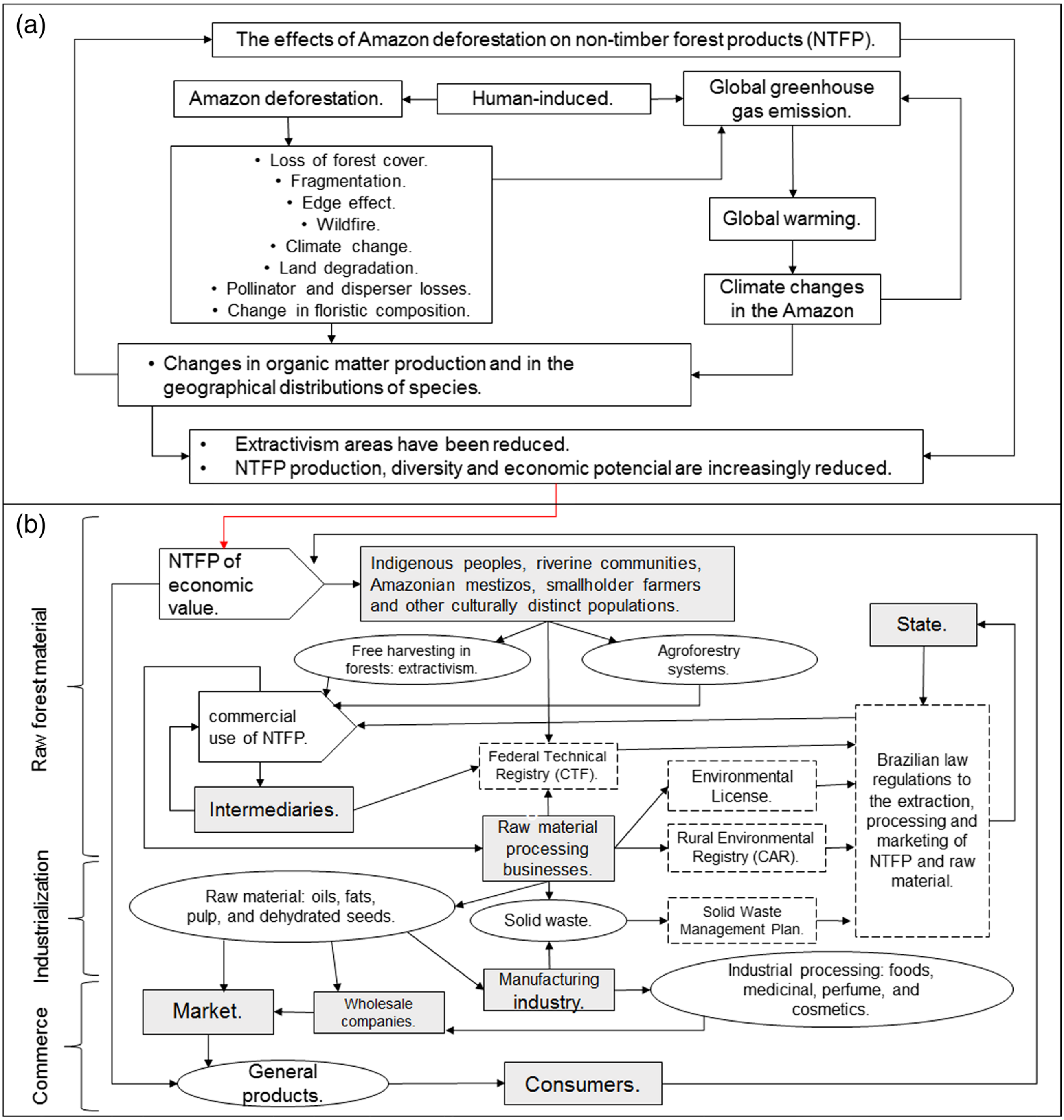
(a)
The effects of Amazon deforestation on non-timber forest products (NTFP).
Amazon deforestation.
Human-induced.
Global greenhouse gas emission.
• Loss of forest cover.
• Fragmentation.
• Edge effect.
• Wildfire.
• Climate change.
• Land degradation.
• Pollinator and disperser losses.
• Change in floristic composition.
Global warming.
Climate changes in the Amazon
• Changes in organic matter production and in the geographical distributions of species.
• Extractivism areas have been reduced.
• NTFP production, diversity and economic potencial are increasingly reduced.
(b)
Raw forest material
Industrialization
Commerce
NTFP of economic value.
Indigenous peoples, riverine communities, Amazonian mestizos, smallholder farmers and other culturally distinct populations.
State.
Free harvesting in forests: extractivism.
Agroforestry systems.
commercial use of NTFP.
Federal Technical Registry (CTF).
Brazilian law regulations to the extraction, processing and marketing of NTFP and raw material.
Environmental License.
Intermediaries.
Raw material processing businesses.
Rural Environmental Registry (CAR).
Raw material: oils, fats, pulp, and dehydrated seeds.
Solid waste.
Solid Waste Management Plan.
Manufacturing industry.
Industrial processing: foods, medicinal, perfume, and cosmetics.
Market.
Wholesale companies.
General products.
Consumers.

Fig. 7 The interconnection between deforestation and non-timber forest products (NTFP) supply chains in the Amazon is represented with a red arrow. **a** Framework of deforestation effects on NTFP. **b** Representation of supply chains for Amazon plants indicating the stages and flows of raw material production, industrialization, and commercialization. Key processes are represented by pentagons, stakeholders are represented by boxes with gray backgrounds, products are represented by oval objects, and environmental requirements are represented by dotted boxes

deforestation rates and cupuassu production suggests that NTFP production in agroforestry systems is more sustainable for both people and businesses. The annual NTFP productivity is higher and more predictable in agroforestry systems compared to areas undergoing extractivist activities (Homma 2014; Damaceno and Lobato 2019). The presence of both acai berry (Fig. 4a) and Brazil nut (Fig. 4c) NTFP production in municipalities with higher deforestation rates has been linked to agroforestry systems (Bolfe and Batistella 2011; Homma 2014; IBGE

2019a). However, the lack of both forest restoration and agroforestry systems may explain the greater negative correlations detected between deforestation and both andiroba (Fig. 4b) and tonka bean (Fig. 4d) in the most deforested municipalities (Table 1). Therefore, if native vegetation is not recovered, deforestation can weaken supply chains for over 20 years (Laurance et al. 2002; Almeida et al. 2019).

No relationship was observed between deforestation and the presence of businesses that process raw material in the investigated municipalities until 2017. This indicates that businesses are succeeding in their NTFP and raw material procurement and logistics strategies. In fact, indicating that businesses are creating new strategies to secure NTFP delivery, Antunes et al. (2021) demonstrated a positive relationship between distance and community gains when assessing the cosmetics supply chain. In addition to rudimentary artisanal methods and equipment, only 15% of the investigated municipalities have the infrastructure and technologies required to process raw material. However, deforestation rate increases (Soares-Filho et al. 2006; Gomes et al. 2019) may continue to decrease NTFP production, and this non-relationship between deforestation and businesses ($p = 0.09$) may not be maintained. This would represent a future with fewer people and businesses acting in the production of NTFP and raw material for the forest's bioeconomy.

The data and information employed herein were obtained from official and recognized sources (IBGE 2017a, b; INCT-MC 2017). However, other municipalities not identified in the mapping applied herein are a possibility. This may be the case for cupuassu production, given the lack of official information on the agricultural production and forest extraction for this species. In addition, the non-detection of municipalities in this regard may also be due to small volumes, rudimentary production methods, and the absence of formal records. Additional studies are required to better understand supply chains. Future investigations can contribute to a better understanding of how climate change (i.e., drought, flooding, global warming, and savannization (Sampaio et al. 2007; Salazar et al. 2007; Lovejoy and Nobre 2018; IPCC 2018)) have modified both NTFP and raw material production in the Amazon.

Conclusions

Deforestation significantly reduced the NTFP production of most investigated species. The findings indicate that (a) NTFP production of acai berry and Brazil nut is higher, even with almost complete deforestation observed in the investigated municipalities, although these NTFP productions tend to decrease with increasing deforestation rates; (b) tonka bean and andiroba NTFP supply chains are highly threatened by deforestation; and (c) the production of cupuassu NTFP and the presence of raw material processing businesses were not associated with deforestation until 2017. Without the presence of forest restoration efforts employing agroforestry systems, the social and economic activities of both people and businesses are at risk, and NTFP production and diversity are increasingly reduced by Amazon deforestation.

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